

## Mineral Assemblages of the Sediments of the Ala Wai Canal and Its Drainage Basins, O'ahu, Hawai'i<sup>1</sup>

POW-FOONG FAN,<sup>2</sup> ROANNA NG,<sup>3</sup> AND DEANNA REMULAR<sup>4</sup>

**ABSTRACT:** To understand the origin of the mineralogy of the sediments in the Ala Wai Canal, 20 soil and stream sediment samples were collected from Mānoa, Pālolo, and Makiki Valleys. X-ray diffraction analysis was used to determine mineralogical composition. Four mineral assemblages are recognized: plagioclase from mechanical weathering present in Makiki Valley and pyroxene, olivine, plagioclase, and ilmenite in Mānoa and Pālolo Valleys; (2) maghemite, hematite, and kaolinite present in all three valleys from chemical weathering and gibbsite and goethite in Mānoa Valley and goethite in Pālolo Valley; (3) quartz in all three valleys from aeolian deposition; and (4) pyrite, calcite, and aragonite in the Ala Wai Canal, and kaolinite and gibbsite derived from the watershed studied.

THE ALA WAI CANAL, which extends along the landward side of Waikīkī, was constructed in 1927 to prevent flooding of Waikīkī. Makiki, Mānoa, and Pālolo Streams drain into the canal. These drainage basins are located in the long spurs of the southwestern Ko'olau Mountains sloping gently from mountain crest to sea along southern O'ahu. To understand the origin of the mineralogy of the sediments in the Ala Wai Canal, 14 soil samples from Makiki, Mānoa, and Pālolo Valleys and six stream samples from Makiki, Mānoa, and Pālolo Streams were collected (Figure 1) and analyzed for their mineralogical content. Mānoa and Pālolo Valleys are two of the series of amphitheater-headed valleys developed along the slope of the 2.6-million-yr-old Ko'olau range. Tantalus, Round Top, and Sugarloaf erupted 67,000 yr ago (Gramlich et al. 1971) with

Tantalus as the head of Makiki Valley. Sugarloaf with its two craters formed the separation between Makiki and Mānoa Valleys. The nephelinite lava from Sugarloaf cascaded down Mānoa Valley and continued into lower Mānoa Valley, blocking Mānoa Stream. The new course of Mānoa Stream is located on the east side of the valley (Macdonald et al. 1983).

Pālolo Stream initially flowed toward Waikīkī and into the ocean. Lava from the growth of the 285,000-yr-old Kaimukī dome (Gramlich et al. 1971) blocked the flow of Pālolo Stream, causing it to flow westward and join Mānoa Stream entering Waikīkī to the ocean. In recent time, Makiki, Mānoa, and Pālolo Streams have been engineered to drain into the Ala Wai Canal (Glenn and McMurtry 1995).

The rainfall record in centimeters/year of the Makiki, Mānoa, and Pālolo Valleys is listed in Table 1. Makiki Valley has 97 cm/yr near the entrance compared with 381 cm/yr at the head of the valley. Mānoa Valley has 66 cm/yr near its entrance compared with 406 cm/yr at the head of the valley. Pālolo Valley has 89 cm/yr near its entrance compared with 333 cm/yr at the head of the valley. These three valleys have an average of 84 cm/yr near the entrance of the valleys and 290 cm/yr at the head of the valleys.

<sup>1</sup>University of Hawai'i School of Ocean and Earth Science and Technology contribution no. 3854. Research supported by National Science Foundation Young Scholars Program Grant RCD-9055108. Manuscript accepted 23 January 1995.

<sup>2</sup>Department of Geology and Geophysics, University of Hawai'i at Mānoa, Honolulu, Hawai'i 96822.

<sup>3</sup>Moanalua High School, 2825 Ala Ilima Street, Honolulu, Hawai'i 96818.

<sup>4</sup>Waipahu High School, 94-1211 Farrington Highway, Waipahu, Hawai'i 96797.

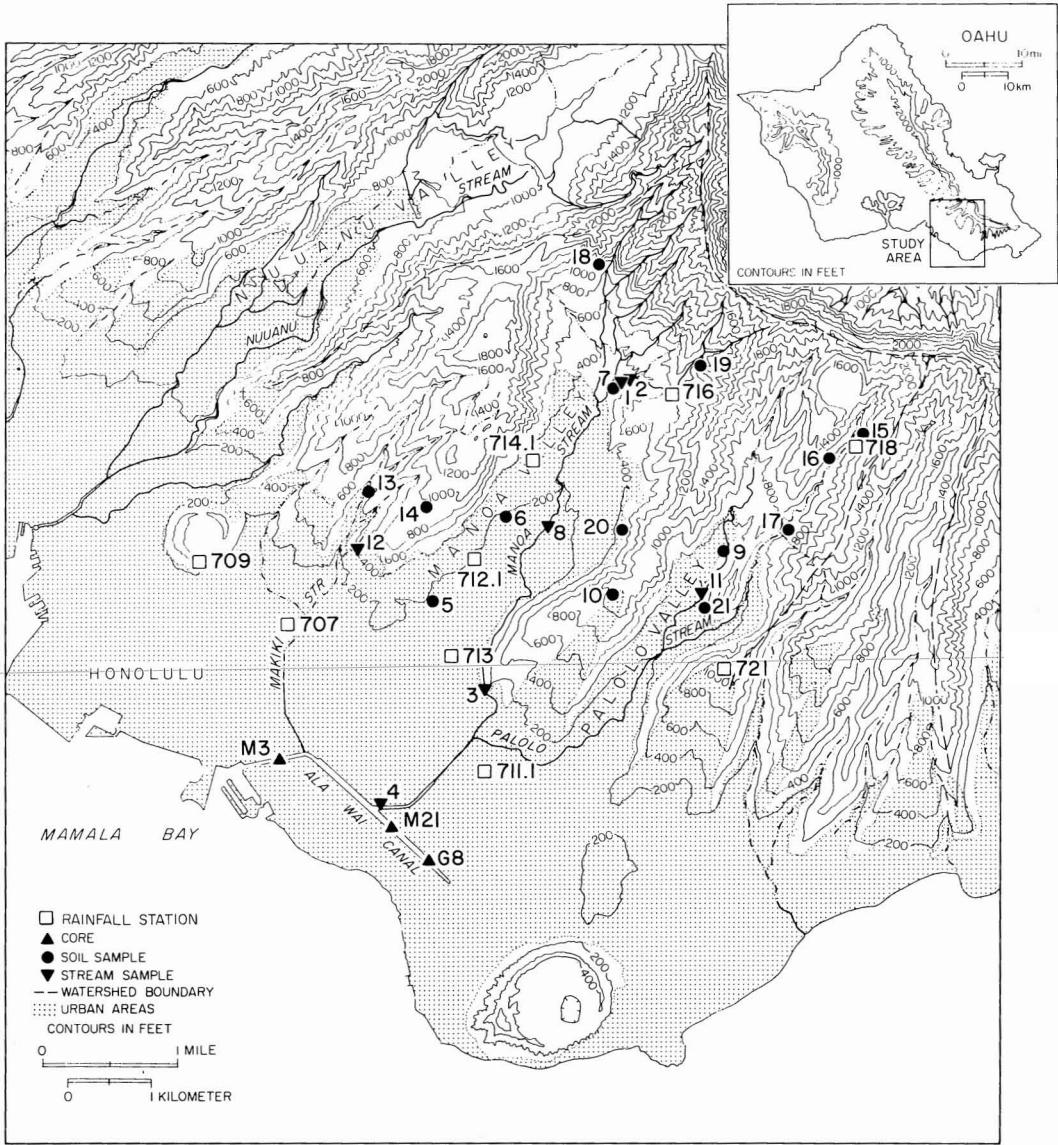


FIGURE 1. Sediment and soil locations in the Ala Wai Canal and its drainage basins.

The rocks of the Ko'olau Volcano consist of mostly tholeiitic basalts. Petrologically, the Ko'olau basaltic rocks are rather uniform. Phenocrysts of olivine, orthorhombic pyroxene, and plagioclase constitute up to 50% of the rocks. Groundmass minerals are feldspar, olivine, orthorhombic pyroxene,

augite, magnetite, ilmenite, apatite, and glass (Wentworth and Winchell 1947).

Intensity of weathering of basaltic lava and ash of the Hawaiian Islands is closely related to rainfall (Figure 2) (Sherman 1952a, Johnsson et al. 1993). Primary minerals are altered to montmorillonite when the annual

TABLE 1  
RAINFALL DATA FOR MAKIKI, MĀNOA, AND  
PĀLOLO VALLEYS

VALLEY	STATION <sup>a</sup>	CM/YR
Makiki	707	95.61
	709	97.31
Mānoa	711.1	65.86
	712	172.77
	713	99.26
	714	258.42
	715	67.79
	716	366.85
Pālolo	718	333.17
	721	108.76

SOURCE: Commission on Water Management, State of Hawai'i, Department of Land and Natural Resources (Giambelluca et al. 1986).

<sup>a</sup>For station locations, see Figure 1.

rainfall is below about 101 cm/yr. Kaolinite or halloysite is predominant between 100 and 200 cm/yr, and goethite and gibbsite are dominant above 200 cm. Formation of goethite is most favorable under alternately wet and dry conditions, whereas gibbsite forms under a continuously wet climate. Bates (1962) showed that plagioclase alters to halloysite and volcanic glass yields allophane with alumina and silica gels. Olivine alters to montmorillonite and ferric hydrates and gels. Gibbsite and ferric hydrates are the final products of very intense weathering.

#### MATERIALS AND METHODS

Soil samples were taken from selected locations in the watershed area. A hole 0.09 m<sup>2</sup> was dug into the ground at the sample site where samples were taken at 10-cm to 50-cm intervals. One soil sample from Maikiki (13) was taken at 100 cm.

Watershed samples were passed through a 1000- $\mu$ m sieve and oven dried at 60°C to remove moisture. Stream sediment samples were wet sieved into two size fractions: 1000 to 45  $\mu$ m and <45  $\mu$ m. Ala Wai Canal sediment samples were dried at 60°C and then reground before X-ray diffraction analysis. X-ray diffraction patterns were made on an automatic diffractometer (Scintag PAD V),

using CuK $\alpha$  radiation at a setting of 40 ma and 45 kv. Scans were made from 2 to 70° 2 $\theta$  at 5° per minute. Semiquantitative analysis by the methods of Fan and Rex (1972) was used to determine the relative abundance of minerals by using peak height calibration factors for the various phases.

Halloysite is a member of the kaolinitic suite of minerals, which have similar X-ray diffraction (XRD) patterns and require detailed analysis to identify them. In this study halloysite and kaolinite are included as kaolinite.

Magnetite and maghemite ( $\gamma$ Fe<sub>2</sub>O<sub>3</sub>) have similar XRD patterns and are difficult to differentiate. Less than 5% of magnetite and ilmenite in Hawaiian basalt (Winchell 1947) probably has undergone weathering. The magnetite in soil could be very fine-grained and is probably oxidized to maghemite. Products of pedogenesis are usually classified as maghemite (Taylor 1987, Schwertmann and Taylor 1989). In this study, the term maghemite is used rather than magnetite.

Montmorillonite and mixed-layered clay minerals are probably present in soil samples from Makiki, Mānoa, and Pālolo Valleys (Johnsson et al. 1993). The XRD procedure used in this study was unable to detect their presence. Additional chemical and heat treatment and slower XRD scanning speed are needed for their identification.

#### RESULTS AND DISCUSSION

Eight X-ray diffraction patterns (Figures 3 and 4) of three soil samples (7, 10-4, and 14-2), two stream samples (3 and 11), and three Ala Wai Canal sediment samples (M-3, M-5, and G-8-20) were selected to represent the end member mineral assemblages of the soils and sediments of the Ala Wai Canal and its drainage basins.

The geological age of Makiki Valley is about 2 million yr younger than that of Mānoa and Pālolo Valleys (Macdonald et al. 1983). The soil samples (13 and 14) belong to the Inceptisols order and are weakly developed, natural horizons in young soils (Foote et al. 1972). Quartz, the aeolian fraction

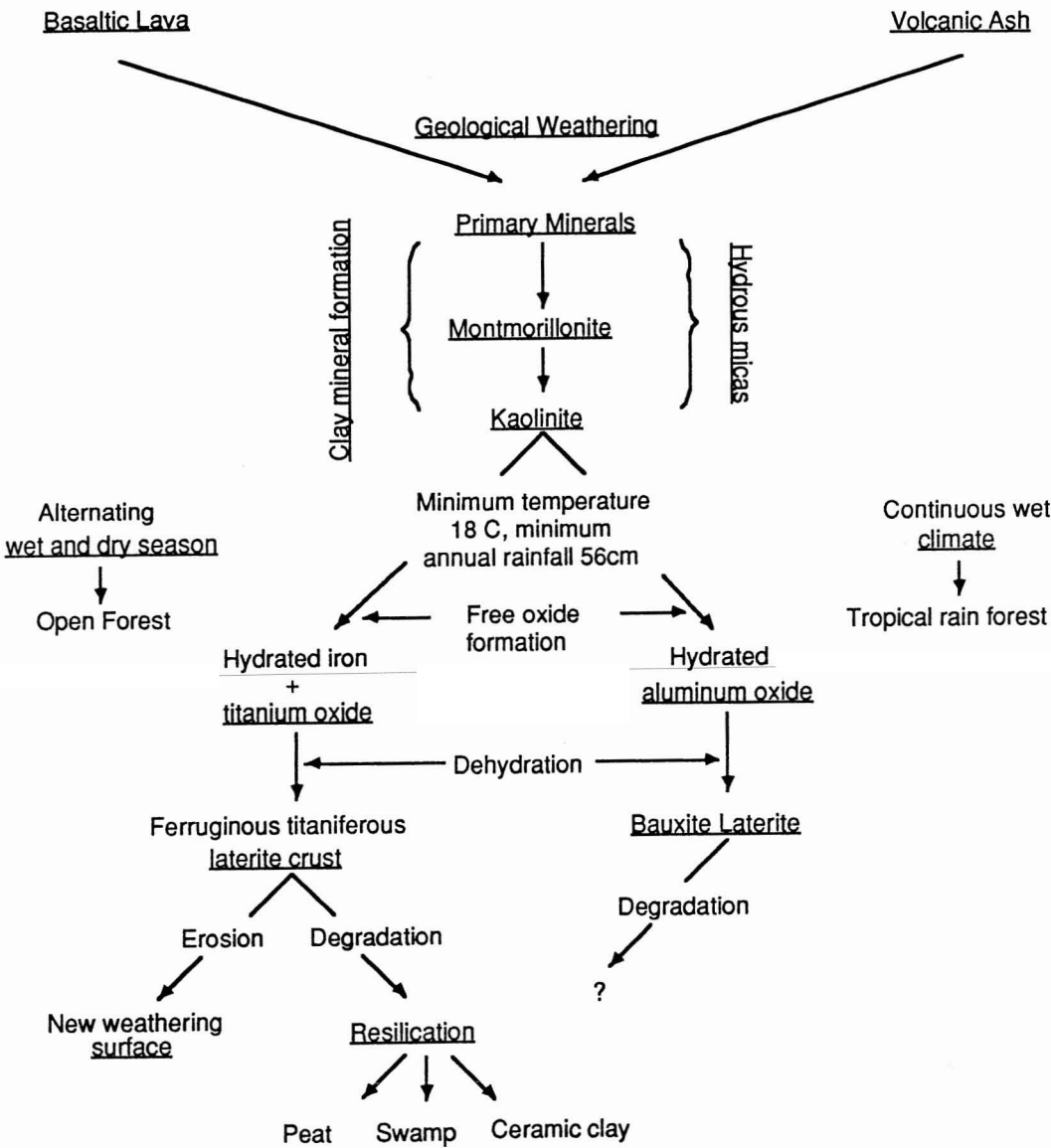


FIGURE 2. Outline of weathering of the Hawaiian Islands (from Sherman 1952a).

of the soils, occurs near the surface of the Hawaiian soil profile (Jackson et al. 1971, Gavenda 1989). Quartz is present in the Makiki Stream sediment sample (12). Kaolinite, gibbsite, anatase, maghemite, and hematite are the weathering products of basalt. Maghemite has been shown to develop from

the dehydration of colloidal hydrated iron oxides from Hawaiian soils (Matsusaka and Sherman 1960). Anatase is generally formed from weathering of titanium-bearing silicates (Loughnan 1969). Sherman (1952b) identified anatase as a secondary product of tropical weathering in Hawaiian soils. Plagioclase,



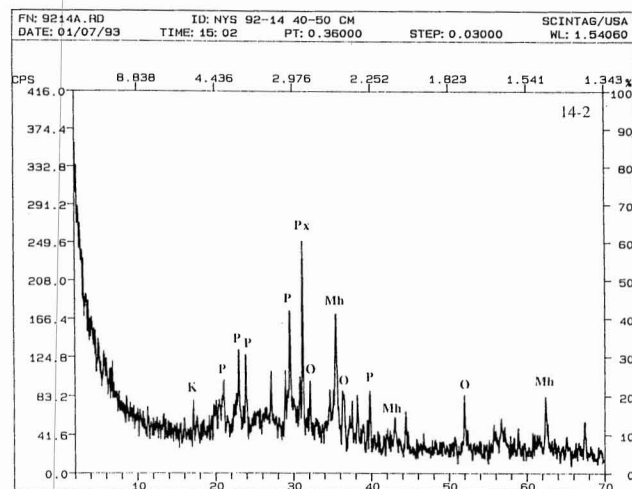
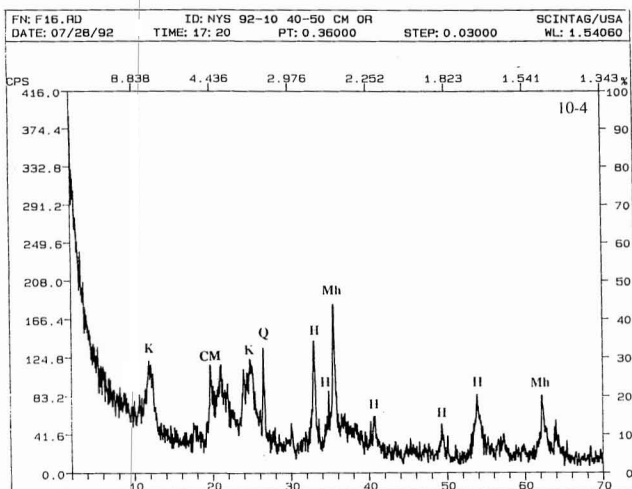
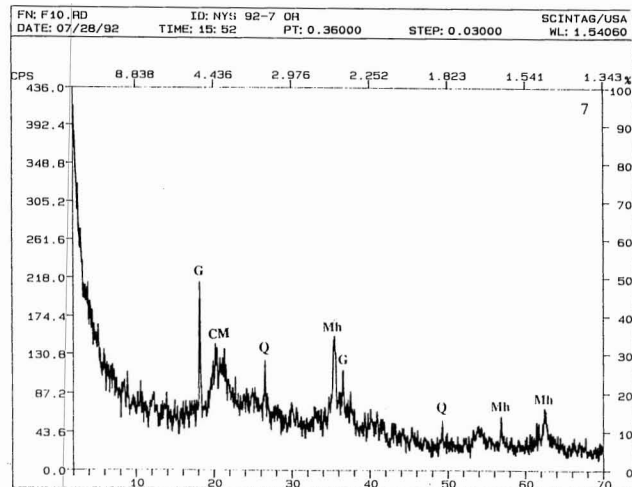
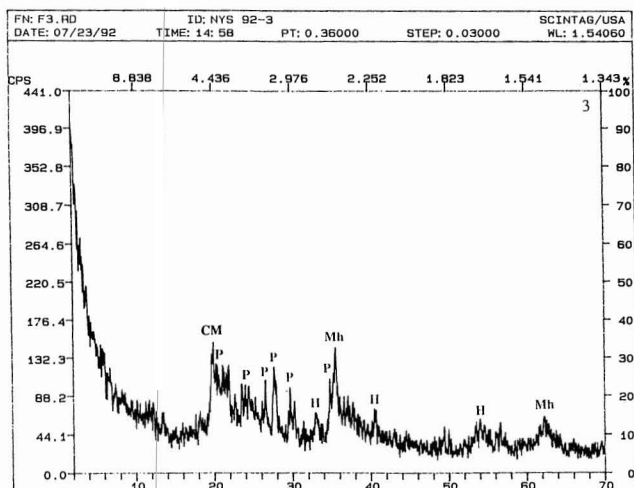


FIGURE 3. X-ray diffraction patterns of selected soil and sediment samples from Makiki, Mānoa, and Pālolo Valleys. Vertical axes in counts per second (CPS) and horizontal axes in  $2\theta$ . A, aragonite; C, calcite (undifferentiated); CM, clay minerals (undifferentiated); G, gibbsite; H, hematite; Ha, halite; K, kaolinite; Mh, maghemite; P, plagioclase; Px, pyroxene; Py, pyrite; Q, quartz.

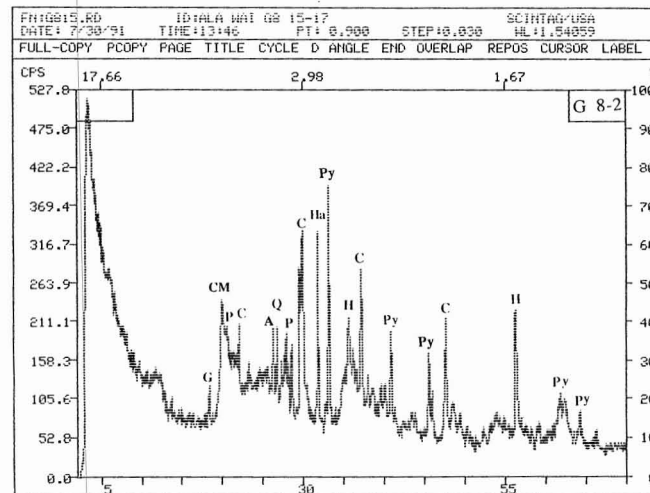
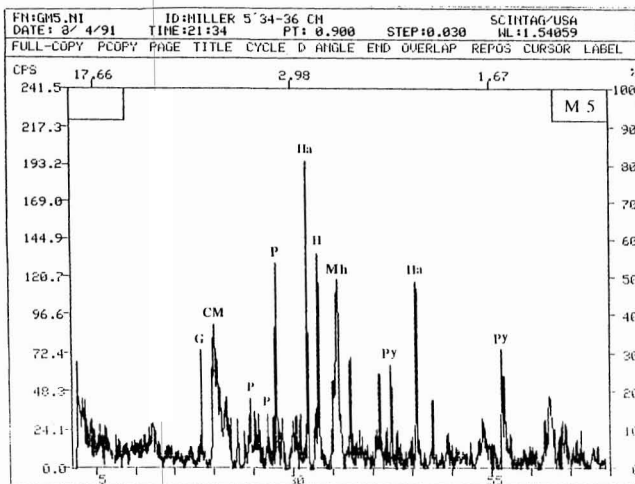
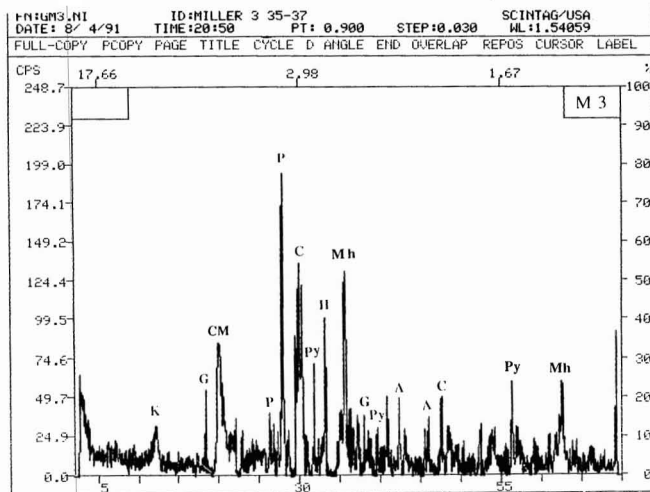
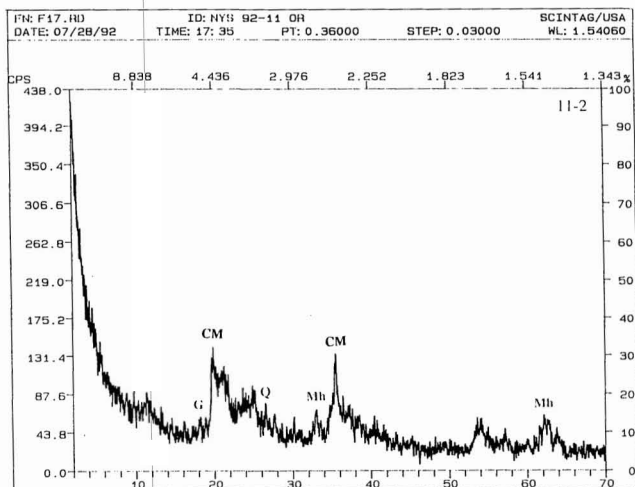


FIGURE 4. X-ray diffraction patterns of selected sediment samples from Pālolo Stream and the Ala Wai Canal. Vertical axes in counts per second (CPS) and horizontal axes in  $2\theta$ . See Figure 3 for explanation of symbols.

pyroxene, and olivine are the products of mechanical weathering that are present in the soil profiles (14-1, 14-2).

The soil samples collected in Mānoa Valley belong to two soil orders: (1) Inceptisols—sample nos. 5, 6, 7, 19, and 29; and (2) Ultisols—sample no. 18. The Ultisols originate in wet climates from strongly weathered parent material. Leaching removes most of the cations from the soil horizons, leaving an argillic horizon in the subsoil (Foote et al. 1972). The soils of Mānoa Valley are high in secondary minerals such as maghemite, kaolinite, and gibbsite. Mechanical weathering products such as plagioclase and pyroxene are present in soil sample 20-2, and olivine is present in soil sample 5. Both of the soil samples are located near the entrance of Mānoa Valley (nos. 5 and 20) where annual rainfall is 66 cm/yr. Ilmenite is present in all of the Mānoa soil samples. Chemical weathering there is not as intense as at the head of Mānoa Valley where the annual rainfall reaches 406 cm/yr. Gibbsite is present near the head of the valley (7, 18, and 19). Sherman et al. (1967), in their study of the bauxitic Hāli'i soils from Kaua'i, reported the crystallization of amorphous iron oxides as possible lepidocrocite and total maghemite as predicted by Tamura and Jackson (1953). Sosman and Posnjak (1925) reported that lepidocrocite could dehydrate to maghemite, and goethite to hematite. Ilmenite, a residual product of mechanical weathering, is present in most samples. Quartz is present in all of the samples from Mānoa Valley.

The soil samples collected in Pālolo Valley belong to two soil orders: (1) Ultisols—samples 15, 16, and 17; and (2) Vertisols—samples 9, 10, and 21. The Vertisols order is usually black and high in clay, and is also known as the Gray Hydromorphic Soils (Foote et al. 1972). The mineral assemblages of the soil samples from Pālolo Valley are similar to those of the soil samples from Mānoa Valley, with secondary minerals—maghemite, hematite, and kaolinite—in most samples. Goethite and gypsum are found in some samples. Gibbsite is very abundant at the head of Mānoa Valley but only found in

samples 16-2 and 16-3, near the head of Pālolo Valley, where the rainfall is around 330 cm/yr. Ilmenite and quartz are present in all samples. The presence of quartz in all surface samples and to depths of 50 cm indicates that the soils were exposed a considerable time to collect the aeolian dusts.

The Makiki Stream samples contain quartz and maghemite, which are also found in the Makiki soil samples. Ilmenite is unique to the stream sample and could be derived from soils outside the sampling area.

The Mānoa Stream samples 1 and 2 are from the head of the valley. They reflect high rainfall and intense chemical weathering products: maghemite, gibbsite, and goethite. Samples from lower Mānoa Stream (3 and 8) reflect a local contribution from Mānoa Stream, such as clay minerals, hematite, gypsum, plagioclase, and pyroxene.

The Pālolo Stream samples (11-2) reflect the intense chemical weathering processes of this area. The sediment sample consists of maghemite, kaolinite, and some quartz. The stream sample 11-1 consists of kaolinite, gibbsite, and maghemite.

Stream sediment sample 4 was taken at Mānoa-Pālolo Stream before it enters the Ala Wai Canal. This sample consists of hematite, maghemite, kaolinite, and gibbsite; it is a fair representation of the major minerals derived from Mānoa and Pālolo Valleys.

Kaolinite and gibbsite are present in most of the Ala Wai Canal samples. They are the products of chemical weathering, and they are abundant in all areas of the watershed studied. Anatase, another chemical weathering product, is present in two samples of Ala Wai Canal core G-8 at 5–7 cm and 98–to 100-cm intervals. Among the mechanical weathering products, only plagioclase is present in all Ala Wai Canal samples. Ilmenite is present in core G-8 at 98–100 cm. Maghemite and hematite are present in all Ala Wai Canal samples. Pyrite is present in all the Ala Wai Canal sediment samples, occurring in fine sediments and as infillings of foraminifera (Glenn et al. 1995, Resig et al. 1995). Pyrite in the Ala Wai Canal sediments is formed by the reaction of detrital iron

# Mineralogy of the Central Honolulu Watershed and the Ala Wai Canal

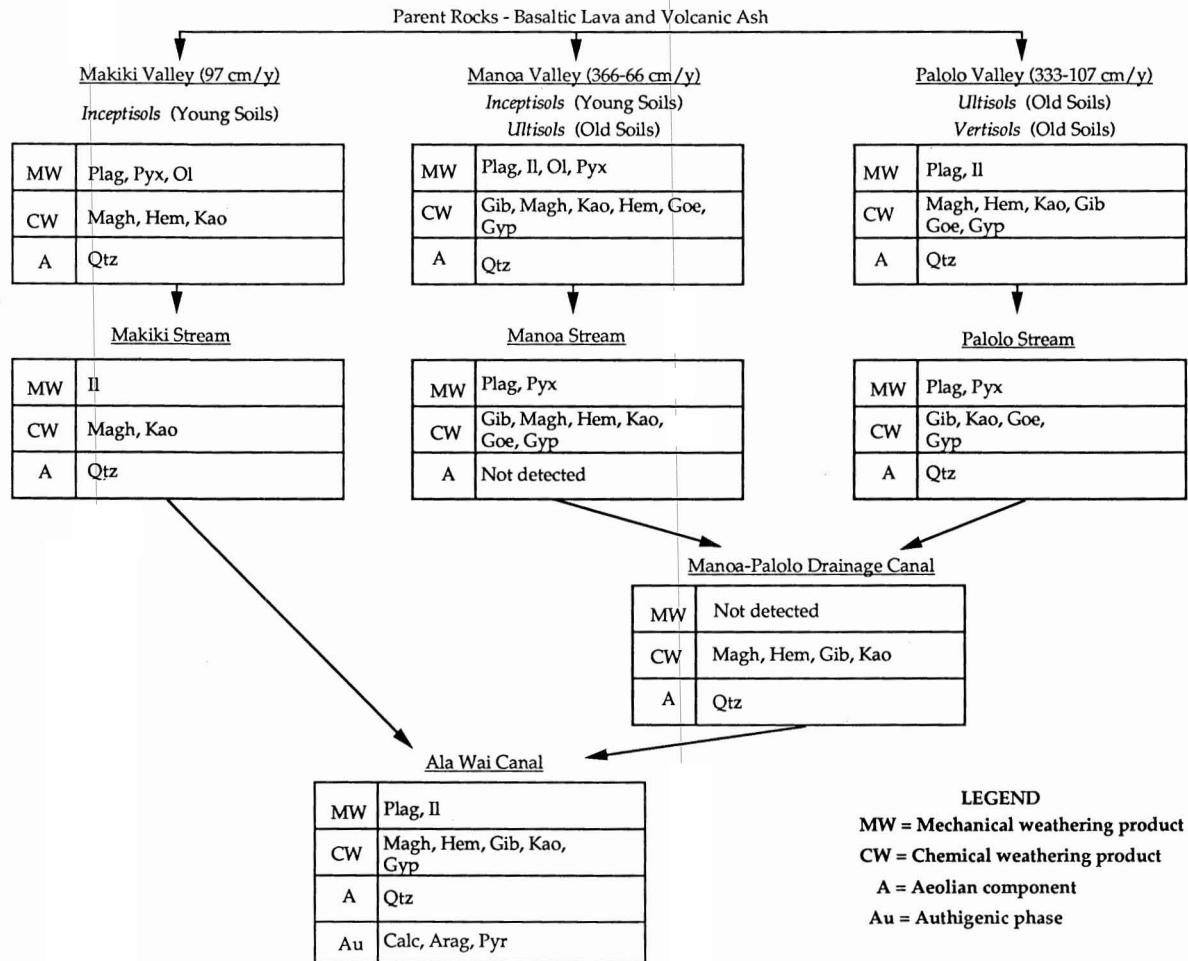


FIGURE 5. Flow diagram of the mineral assemblages of the soils and sediments of the Ala Wai Canal and its drainage basins.

TABLE 2

RELATIVE MINERAL COMPOSITION OF SOIL AND SEDIMENT SAMPLES OF THE ALA WAI CANAL AND ITS DRAINAGE BASINS

										MINERAL COMPOSITION <sup>b</sup>								
LOCATION	NO.	DEPTH (cm)	SOIL <sup>a</sup>	Qtz	Ol	Pyx	Il	An	Plag	Kao	Gib	Magh	Hem	Goe	Pyr	Gyp	Calc	Arag
Mānoa Stream	1			C <sup>c</sup>					P		P	C		P				
	2			C							P	P	P					
	3			C		P			P			P	P					
M-P Streams <sup>d</sup>	4									P	P	C	C					
Mānoa Valley	5		Inc		P		P			P		C	P					
	6-1	0-10	Inc	C			P					P						
	6-2	10-20	Inc	C			P					C						
	7		Inc								A	C						
Mānoa Stream	8										P	C	P	P			T	
Pāloalo Valley	9		Ver	C								C						
	10-1	0-10	Ver				P			P		P	C			P		
	10-2	10-20	Ver							P		C		C				
	10-3	30-40	Ver	C			P					P	P					
	10-4	40-50	Ver	C						P		P	C					
Pāloalo Stream	11-1	Silt				P			P		C	P						
	11-2	0-10								P		A						
Makiki Stream	12			P			P					A						
Makiki Valley	13-1	0-10	Inc	C						P		C						
	13-2	90-100	Inc							P		C		C				
	14-1	0-10	Inc			C			C	P		C						
	14-2	40-50	Inc		P	C			C			C						
Pāloalo Valley	15-1	0-15	Ult				P		P	P		C	P				T	
	15-2	20-30	Ult	P					P	P		C	P	P				
	15-3	40-50	Ult	P			P		T	P		P	P					
	16-1	0-10	Ult	P			P			P		C	P				T	
	16-2	10-20	Ult				P			P	P	C	C				T	
	16-3	40-50	Ult				P			P	P		P	P			T	
	17-1	0-10	Ult				P			P		T	P	P				
	17-2	20-30	Ult	P			P			P		P	P	P			P	
	17-3	40-50	Ult	T			P			P		C	P	P			T	
Mānoa Valley	18-1	0-10	Ult	P			P			T	A	P	P	P				
	18-2	20-30	Ult	T			P			P	C	P	P	P				
	18-3	50-60	Ult	P			P			T	P	P	T	T				
	19-1	0-10	Inc				P			P	P	C	P	P			T	
	19-2	20-30	Inc	P			P			P	P	P	P	P			P	
	19-3	40-50	Inc	T			P			T	P	C	P	P				





## ACKNOWLEDGMENTS

We gratefully acknowledge the support of the National Science Foundation, which made this research possible. We would like to acknowledge the cooperation of Gary McMurtry in collecting soil and sediment samples and Craig Glenn, Gary McMurtry, and Eric De Carlo for collecting core samples from the Ala Wai Canal. We thank Jane Tribble and Clark Sherman for the use of the X-ray diffractometer, Jane Tribble for reviewing the manuscript, and Craig Glenn for preparing Figure 5.

## LITERATURE CITED

- BATES, T. B. 1962. Halloysite and gibbsite formation in Hawaii. *Clays Clay Miner.* 9:307-314.
- BERNER, R. A. 1984. Sedimentary pyrite formation: An update. *Geochim. Cosmochim. Acta* 48:605-615.
- . 1985. Sulfate reduction, organic matter decomposition and pyrite formation. *Philos. Trans. R. Soc. Lond. A, Math. Phys. Sci.* 315:25-38.
- FAN, P.-F., and R. W. REX. 1972. X-ray mineralogy studies, Leg. 14. Pages 677-726 in D. E. Hayes, A. C. Pimm, J. P. Beckmann, W. E. Benson, W. H. Berger, P. H. Roth, P. R. Supko, and U. von Rad, Initial Rep. DSDP 14. U.S. Government Printing Office, Washington, D.C.
- FOOTE, D. E., E. L. HILL, S. NAKAMURA, and F. STEPHENS. 1972. Soil survey of Islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawaii. U.S. Department of Agriculture, Soil Conservation Service in Cooperation with the University of Hawai'i Agriculture Experiment Station. U.S. Government Printing Office, Washington, D.C.
- GAVENDA, R. T. 1989. Soil genesis and landscape evolution in central Oahu, Hawaii. Ph.D. diss., University of Hawai'i at Mānoa, Honolulu.
- GIAMBELLUCA, T. W., M. A. NULLET, and T. A. SCHROEDER. 1986. Rainfall atlas of Hawaii. Department of Land and Natural Resources, Division of Water and Land Development, State of Hawai'i, Report R76: 267.
- GLENN, C. R., and G. M. MCMURTRY. 1995. Scientific studies and history of the Ala Wai Canal, an artificial tropical estuary in Honolulu. *Pac. Sci.* 49:307-318.
- GLENN, C. R., S. RAJAN, G. M. MCMURTRY, and J. BENAMAN. 1995. Geochemistry, mineralogy, and stable isotopic results from Ala Wai estuarine sediments: Records of hypereutrophication and abiotic whittings. *Pac. Sci.* 49:367-399.
- GRAMLICH, J. W., V. A. LEWIS, and J. J. NAUGHTON. 1971. Potassium-argon dating of Holocene basalts of the Honolulu Volcanic Series. *Geol. Soc. Am. Bull.* 82:1399-1404.
- JACKSON, M. L., T. W. M. LEVELT, J. K. SYERS, R. W. REX, R. N. CLAYTON, G. D. SHERMAN, and G. UEHARA. 1971. Geomorphological relationships of tropospherically derived quartz in the soils of the Hawaiian Islands. *Soil Sci. Soc. Am. Proc.* 35:515-525.
- JOHNNSSON, M. J., S. D. ELLEN, and M. A. MCKITTRICK. 1993. Intensity and duration of chemical weathering: An example from soil clays of the southeastern Koolau Mountains, Oahu, Hawaii. Pages 147-170 in M. J. Johnsson and A. Basu, eds. *Processes controlling the composition of clastic sediments*. *Geol. Soc. Am. Spec. Pap. (Reg. Stud.)* 284.
- LOUGHNAN, F. C. 1969. *Chemical weathering of silicate minerals*. Elsevier, New York.
- MACDONALD, G. A., A. T. ABBOTT, and F. L. PETERSON. 1983. *Volcanoes in the sea: The geology of Hawaii*, 2nd ed. University of Hawai'i Press, Honolulu.
- MATSUSAKA, Y., and S. D. SHERMAN. 1960. Magnetism of iron oxide in Hawaiian soils. *Soil Sci.* 91:239-245.
- RESIG, J. M., K. MING, and S. MIYAKE. 1995. Foraminiferal ecology, Ala Wai Canal, Hawai'i. *Pac. Sci.* 49:341-366.
- SCHWERTMANN, U., and R. M. TAYLOR. 1989. Iron oxides. Pages 379-438 in J. B. Dixon and S. B. Weed, eds. *Minerals in soil environments*, 2nd ed. Soil Science Society of America, Madison, Wisconsin.

- SHERMAN, G. D. 1952*a*. The genesis and morphology of the alumina-rich laterite clays. Pages 154–161 in *Problems of clay and laterite genesis*. American Institute of Mining Metallurgical Engineers, New York.
- . 1952*b*. The titanium content of Hawaiian soils and its significance. *Soil Sci. Soc. Am. Proc.* 16:15–18.
- SHERMAN, G. D., J. G. CADY, H. IKAWA, and N. E. BLOMBERG. 1967. Genesis of the bauxitic Haliu soils. *Hawaii Agric. Exp. Stn. Tech. Bull.* 56.
- SOSMAN, R. S., and E. POSNJAK. 1925. Ferromagnetic ferric oxide, artificial and natural. *J. Wash. Acad. Sci.* 15:329–342.
- TAMURA, T., and M. L. JACKSON. 1953. Structural and energy relationships in formation of iron and aluminum oxide, hydroxides and silicates. *Science* (Washington, D.C.) 117:381–383.
- TAYLOR, R. M. 1987. Non-silicate oxides and hydroxides. Pages 129–201 in A. C. D. Newman, ed. *Chemistry of clays and clay minerals*. Longman Scientific & Technical. Mineralogical Society.
- WENTWORTH, C. K., and H. WINCHELL. 1947. Koolau basalt series, Oahu, Hawaii. *Geol. Soc. Am. Bull.* 58:49–78.
- WINCHELL, H. 1947. Honolulu Series, Oahu, Hawaii. *Geol. Soc. Am. Bull.* 58:1–48.